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EXPERIMENTAL VERIFICATION OF BUILDING CONTROL USING ACTIVE BRACING SYSTEM

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SUMMARY

The objective of this paper is to examine the effectiveness of some control algorithms which will be implemented through experimental verification of a seismic-excited full-scale building. A full-scale 3-storey steel building with active bracing control system was tested at a three-dimensional shaking table of NCREE, Taiwan. The active bracing control system was installed at the first floor. Three different control algorithms were used for the experimental verification: static-output-feedback LQR control, modal control with direct output feedback, and static-output-feedback with variable gain. It is concluded that within the maximum capacity of the actuator in the experiment all the three control algorithms performed well and almost 50 per cent of displacement as well as the acceleration of each floor response was reduced. Copyright © 1999 John Wiley & Sons, Ltd.

1. INTRODUCTION

When a control system is applied to civil engineering structure to reduce the structural response under earthquake excitation, some critical issues arise even for a simple structure system. The issues include the following: (1) the feasibility and effectiveness of different active control methods, (2) too many degrees of freedom in a real structural system with limited information available from the structural response measurement, and (3) the maximum control force generated by the actuator is limited. To solve the problems the most effective way is to perform the experimental verification of a building subjected to earthquake ground motion and consider the above-mentioned three issues. It is believed that the shaking table test was one of the most effective ways to verify and demonstrate the control theory for active control. In recent years, many control algorithms had been proposed to be effective in structural control such as LQR,[1] predict control,[2] modal control,[3] sliding mode control,[4] H-infinity control,[5] etc. Most of them were tested by numerical simulation and some of them were also verified by experimental studies. Among the experimental studies, researchers used either small-scale model testing on shaking table[3,6–8] or

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full-scale building excited by exciter.[9,10] With small-scale test we could not know whether the active control system is still effective in full-scale test, and using exciter as excitation input could not really represent the actual response of the structure under earthquake excitation. So, to implement the active control system, one needs a full-scale test of a structure on the shaking table and conduct the active control experiments.

The seismic simulator in National Center for Research on Earthquake Engineering (Taiwan), processes six degrees of freedom to simulate earthquake motion in three axes. The size of the shaking table is $5^m \times 5^m$ and its mass 27 ton. Structural model with a maximum payload of 50 ton can be accommodated on the table. The shaking table is driven by 12 hydraulic actuators. The hydraulic power is provided by two electrical pumps and three diesel pumps which offer a total flow rate of 1325 g/min with a work pressure of 210 kg/cm^2, the weight of the shaking table and the structural model is balanced by four static supports. It is a high-performance shaking table. The experimental verification of the active control of structure can be performed on this table.

The purpose of this paper is to conduct the numerical and experimental study of a full-scaled three-storey steel building using active bracing control system as control device and to examine the effectiveness of the control strategies. In this study three different control algorithms will be discussed: (1) modal control with direct output feedback, (2) static-output-feedback LQR control, (3) static-output-feedback LQR control with variable gain. Direct measurement feedback control was developed to replace the full-state feedback control in all of the three full-scale experimental studies.

2. CONTROL STRATEGY DEVELOPMENT

Active control have been used against earthquake excitations in numerical and experimental studies, various control algorithms like LQR, predict control modal control, sliding mode control[4] and H-infinity[5] have been proposed. Each control algorithm has its own feature and direct measurement feedback control can be used with most of them. Consider an n-degree of freedom linear building subjected to seismic excitation. The vector equation is given by (in the state-space form)

$$\dot{Z}(t) = AZ(t) + BU(t) + EW(t) \tag{1}$$

where

$$Z(t) = \begin{bmatrix} X(t) \\ \dot{X}(t) \end{bmatrix}, \quad A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} \underline{0} \\ M^{-1}H \end{bmatrix}, \quad E = \begin{bmatrix} \underline{0} \\ I \end{bmatrix}$$

where A is the system matrix, $U(t)$ is the control force vector and $W(t)$ is the excitation. Since equation (1) represents the dynamics of the complete structure, it is called the full-order system. Define the output vector $\bar{Y}$ as that which contains m measurements ($m < 2n$). The relationship between measurement and the state vector is given by

$$\bar{Y} = CZ(t) \tag{2}$$

where the $C(m \times 2n)$ matrix is referred to as the observation matrix. The discrete form of equation (1) can be expressed as

$$Z[k+1] = A_d Z[k] + B_d U[k] + E_d W[k] \tag{3}$$

where $A_d = \exp[A \cdot \Delta t]$, $B_d = A^{-1}(A_d - I)B$, $E_d = A^{-1}(A_d - I)E$. Based on the system equation of motion with the consideration of the direct output feedback control, three different control algorithms can be developed. Direct output feedback control represents another class of control methods where the control commands are directly generated from sensor signals measured only at limited locations of the controlled structure. The following three control algorithms are all based on the direct output feedback signals.

2.1. *Static-output-feedback LQR control*

The static-output-feedback control is to use the measured output to compute the control force directly. It is different from the dynamic-output-feedback control in which the dynamic condensation was used to reduce the degree of freedom of the structure system and then the predict-type Kalman filter was also used to predict the full-state using measurement. The performance index to be minimized in the static-output-feedback LQR optimal controller is given by:

$$J = Z^{T}(t)QZ(t) + U^{T}(t)RU(t) + \lambda(t)\{AZ(t) + BU(t) - \dot{Z}(t)\} \tag{4}$$

One can obtain a minimization of the performance index J subjected to the constraint results by the following

$$\begin{aligned} \partial J/\partial Z(t) = 0 \;&\Rightarrow\; QZ(t) + A^{T}\lambda(t) + \dot{\lambda}(t) = 0 \\ \partial J/\partial U(t) = 0 \;&\Rightarrow\; U(t) = -R^{-1}B^{T}\lambda(t) \end{aligned} \tag{5}$$

To consider the limited measurements, set $\lambda(t) = PCZ(t) = PY(t)$, where C is the transformation matrix which transfers the state vector to the measurement output and P is an unknown matrix that has to be determined. Equation (5) can be replaced by

$$QZ(t) + A^{T}PCZ(t) + PCAZ(t) - PCBR^{-1}B^{T}PCZ(t) = 0 \tag{6}$$

Set $P_r = PC$, Equation (6) can be reduced to the standard Ricatti equation.

$$Q + A^{T}P_r + P_rA - P_rBR^{-1}B^{T}P_r = 0 \tag{7}$$

In order to find the P_r matrix, a least-square minimization method was used to solve P_r from the equation $P_r - PC = 0$. Then we define another objective function $J_i = (P_iC - P_{ri})\Theta(P_iC - P_{ri})^{T}$. Then through minimization, one obtains

$$P_i = (P_{ri}\Theta C^{T})(C\Theta C^{T})^{-1} \tag{8}$$

where P_i is the ith column from P and P_{ri} is the ith column of P_r and Θ is the weighting factor. Finally, the control force can be obtained:

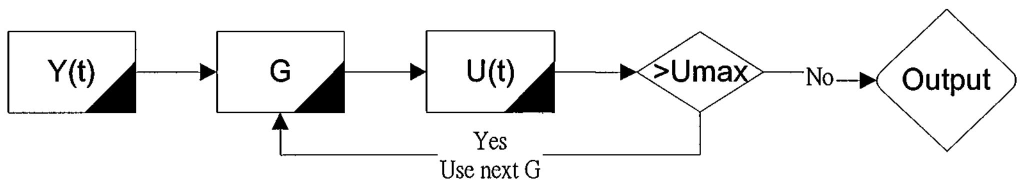
$$U(t) = -R^{-1}B^{T}[(P_r\Theta C^{T})(C\Theta C^{T})^{-1}]Y(t) = GY(t) \tag{9}$$

and P_r can be obtained from the Ricatti equation as shown in equation (7).

2.2. *Static-output-feedback LQR control with variable gain*

Static-output-feedback LQR control with variable gain is designed with the same control algorithm as before but with several levels of prescribed control gains. The control sequence is shown below: The variable gain method must be incorporated with specified control algorithm,

so that the control gain G can be calculated first, $U(t) = GY(t)$. At time $t = k\Delta t$ if $U(t) > U_{max}$ (maximum capacity of the actuator) then the G value will automatically reduce to a lower level of G value at that particular time interval (in the present study five levels of G level were assigned: -220, -190, -175, -165, -160 kg s/cm). In general, if higher control gain was designed, better control effectiveness would have been obtained, but it also needs larger control force. In this method we propose to use the highest control gain and keep the control force under the limited maximum control force (U_{max}). If control force is exceeded, the next lower value of control gain will be used until the control force is under the limit. Using this method the control force can reach bigger value during excitation but never exceed the capacity of the actuator.



2.3. Modal control with direct output feedback (modal control)

Modal control is the method of computing the gain matrix, G, to achieve the desired modal properties, i.e. frequency, damping ratio and modal shape. Direct output feedback control represents another class of control methods, where the control commands are directly generated from the sensor signals measured only at limited locations of controlled structures. Because of limited measurements, one can only assign r modal properties (r is the number of sensors). Herein the sensor signals measure only $\dot{x}_1$ and x_1. Let λ_i and μ_i (where $i = 1 \sim r$) be the assigned eigenvalues and eigenvectors. Therefore the state equation of motion of the control system can be expressed as

$$(A + BGC)\mu_i = \lambda_i \mu_i \tag{10}$$

where C is the transformation matrix which transfers the state vector to the measurement output. Then equation (10) can be separated into two parts as follows:

$$(A_1 + B_1 GC)\mu_i = \lambda_i \mu_i^1 \tag{11}$$

$$(A_2 + B_2 GC)\mu_i = \lambda_i \mu_i^2 \tag{12}$$

where

$$A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \qquad B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \quad \mu_i = \begin{bmatrix} \mu_i^1 \\ \mu_i^2 \end{bmatrix}.$$

The dimensions of A_1 and B_1 are $p \times 2n$, $p \times p$, respectively (p is the number of controllers). Combine the assigned r eigenvalues and eigenvectors in equation (11), to obtain the following matrix form equation:

$$(A_1 + B_1 GC)U_c = Z_c \,\mathrm{diag}(\lambda_i)_c \tag{13}$$

where

$$U_{\mathrm{c}} = [\mu_1, \mu_2, \ldots, \mu_r]_{2n \times r}, \qquad \mathrm{diag}(\lambda_i)_{\mathrm{c}} = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \lambda_r \end{bmatrix}_{r \times r}$$

$Z_{\mathrm{c}} = [z_1, z_2, \ldots, z_r]_{p \times r}$. Then the gain matrix, G, is given by

$$G = B_1^{-1}(Z_{\mathrm{c}}\,\mathrm{diag}(\lambda_i)_{\mathrm{c}} - A_1 U_{\mathrm{c}})(CU_{\mathrm{c}})^{-1} \tag{14}$$

Note that B_1 must be non-singular matrix and r must be an even number. Similarly, equation (12) can be derived by the same procedure as equation (11) and following relationship can be obtained:

$$(\lambda_i I - F)\mu_i^2 = (H + \lambda_i S)\mu_i^1 \tag{15}$$

where $H = A_{21} - SA_{11}$, $F = A_{22} - SA_{12}$, $S = B_2 B_1^{-1}$. Equation (15) implies that not all of the elements in the assigned r eigenvectors can be arbitrary prescribed, but only p elements in each of the eigenvectors can be freely chosen.

To find the suitable eigenvector that satisfies the condition shown in equation (15), a performance index in terms of μ_i and μ_i^{d} is expressed as

$$J = \|\mu_i^{\mathrm{d}} - \mu_i\|^2 \tag{16}$$

where μ_i^{d} is the desired eigenvector. Finally, the best achievable eigenvector, μ_i, can be obtained through minimization of the performance index, equation (16).

3. EXPERIMENTAL RESULTS — ACTIVE BRACING SYSTEM

In order to demonstrate the control effectiveness of the proposed control algorithm on the reduction of relative displacement and absolute acceleration of a real structure, a full-scale steel structure testing was conducted on shaking table. A three-storey single bay (each bay with one active bracing system) steel building with two active brace systems at first floor was used for experimental study, shown in Figure 1. In order to estimate the system characteristics the bare frame of the experimental building was first tested on the shaking table with random excitation (normalized to 50 gal). The time domain sequential regression analysis was used to identify both the stiffness matrix and the damping matrix of the system based on the full-state measurement. The identified structural parameters of the three-storey steel structure were shown in Table I. The control device set-up was arranged in such a way that the active brace system was installed at the first floor and it comprised an actuator connecting with steel tube as a bracing system. The diagram of the experimental set-up in the three-storey steel structure with active brace system at first floor was shown in Figure 1.

3.1. Design of control gain

Consider both the E1 Centro earthquake and Kobe earthquake (normalized to 100 gal) as the input motion from the base of the building. Based on the above-mentioned three control algorithms seven different cases to develop control gains were discussed:

Case 1 (DV1-MOD): Modal control with direct output feedback was used. First floor displacement and velocity are measured as feedbacks. The control parameters for this case was shown in Table II.

Case 2 (DV1-KM): Static-output-feedback LQR control algorithm was used and only the first floor displacement and velocity response were used as the measurement as in case 1. Control parameter Q was assigned similar value of system stiffness matrix and mass matrix. The performance index J in LQR control algorithm denotes the total potential and kinetic energy of the structure to be minimized. Control parameter R was chosen to make the

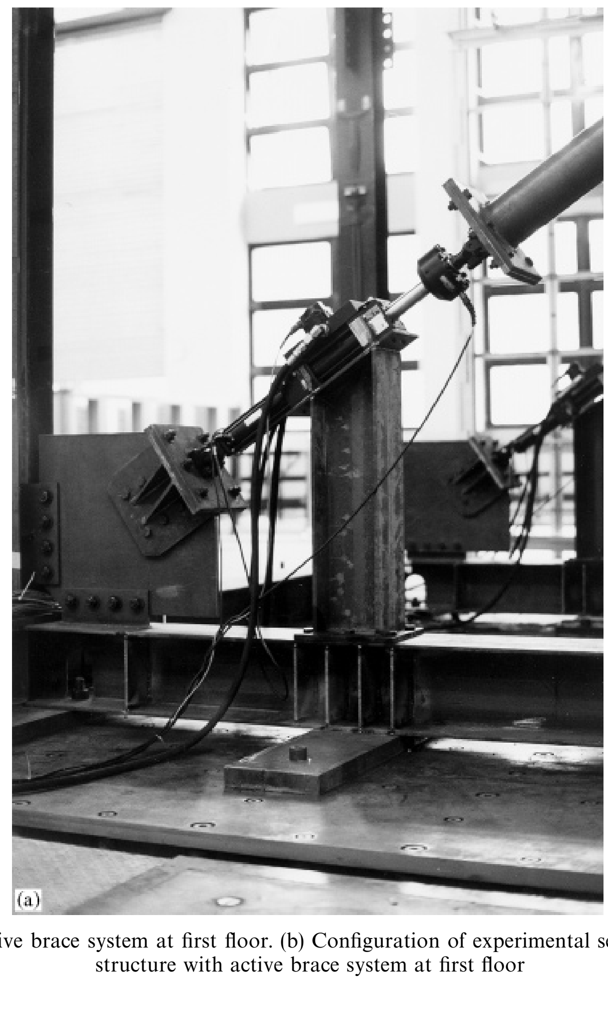
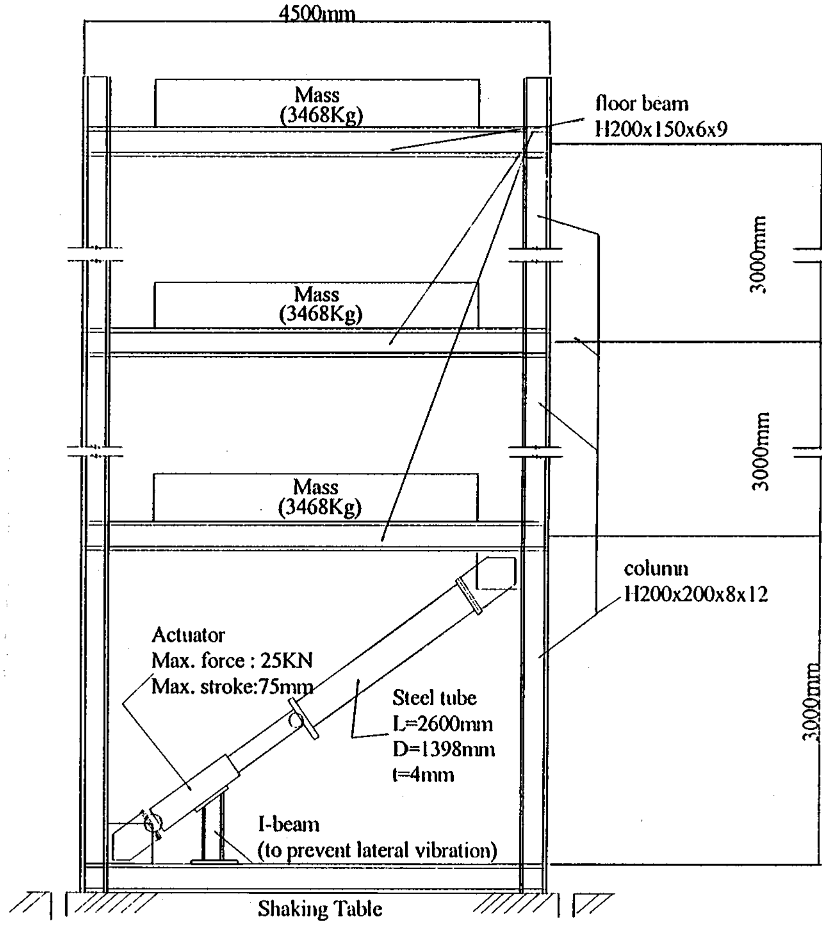


Figure 1. (a) View of active brace system at first floor. (b) Configuration of experimental setup of a three-storey steel structure with active brace system at first floor



(b)

Figure 1. Continued

maximum control force not over 10 kN. All the control parameters for this case are shown in Table III.

Case 3 (DV1-ONE): The same control algorithm as in case 2 was used, but the control parameter Q was no longer assigned to $[K]$-matrix and $[M]$-matrix, but it was replaced by identity matrix as shown in Table IV.

Case 4 (V1-KM): Static output feedback LQR control algorithm was used in this case and considered only first floor velocity response as feedback, and control parameter Q was set to $[K]$-matrix and $[M]$-matrix again. The control parameters were shown in Table V.

Case 5 (FDV-MOD): Modal control with full-state feedback was used in this case.

Case 6 (FDV-KM): LQR control algorithm with full-state feedback was used in this case.

Case 7 (V1-VG): Similar to the static output feedback LQR control (case 4) but consider the variable gain.

3.2. *Results from shaking table test*

To demonstrate the effectiveness of the above-mentioned control algorithms, E1 Centro earthquake data and Kobe (NS-dir.) earthquake data (both are normalized to 100 gal) were used as input motions from case 1 to case 6. Figures 2 and 3 show the comparison of maximum percentage of reduction in floor acceleration and displacement, and the maximum control force for each case of control algorithm. We can see that the proposed three control algorithms using

Table I. Parameter of three-storey steel structure

Mass matrix (kg s/cm)	Damping matrix (kg s/cm)	Stiffness matrix (kg/cm)
$\begin{bmatrix} 11{\cdot}42 & 0 & 0 \\ 0 & 11{\cdot}42 & 0 \\ 0 & 0 & 11{\cdot}12 \end{bmatrix}$	$\begin{bmatrix} 2{\cdot}17 & -0{\cdot}12 & 0{\cdot}1 \\ -0{\cdot}12 & 2{\cdot}41 & -0{\cdot}21 \\ 0{\cdot}1 & -0{\cdot}21 & 2{\cdot}37 \end{bmatrix}$	$\begin{bmatrix} 10\,163 & -5629 & 991 \\ -5629 & 8617 & -4138 \\ 991 & -4138 & 3278 \end{bmatrix}$
Natural frequency (Hz)	(1·096, 3·498, 5·970)	
Damping ratio (%)	(1·41, 0·45, 0·29)	

Table II. Control parameter of case 1 (dv1_mod)

Control gain (kg/m, kg s/m)	(23 415, − 14 576)
Controlled natural frequency (Hz)	(1·07, 3·49, 5·65)
Controlled damping ratio (%)	(15, 30·3, 9·17)
Relative disp. reduction (100 gal E1 Centro)	(60·7%, 60·0%, 57·5%)
Maximum control force (100 gal E1 Centro)	9·1037 kN

Table III. Control parameter of case 2 (dv1_km)

	$Q = \begin{bmatrix} \underline{K} & \underline{0} \\ \underline{0} & \underline{M} \end{bmatrix}, \quad R = 10^{-2\cdot 3},$
Control parameter	$Q_i = \begin{bmatrix} 10^{2\cdot 5} & 1 & 1 & 1 & 1 & 1 \\ 1 & 10^{2\cdot 5} & 0 & 1 & 0 & 0 \\ 1 & 0 & 10^{2\cdot 5} & 1 & 0 & 0 \\ 1 & 1 & 1 & 10^{2\cdot 5} & 1 & 1 \\ 1 & 0 & 0 & 1 & 10^{2\cdot 5} & 0 \\ 1 & 0 & 0 & 1 & 0 & 10^{2\cdot 5} \end{bmatrix}$
Control gain (kg/m, kg s/m)	(− 61 817·52, − 10 159·23)
Controlled natural frequency (Hz)	(1·1656, 3·7237, 5·8844)
Controlled damping ratio (%)	(6·68, 14·93, 10·06)
Relative disp. reduction (100 gal E1 Centro)	(52·37%, 45·84%, 44·75%)
Maximum control force (100 gal E1 Centro)	9·0887 kN

Table IV. Control parameter of case 3 (dv1_one)

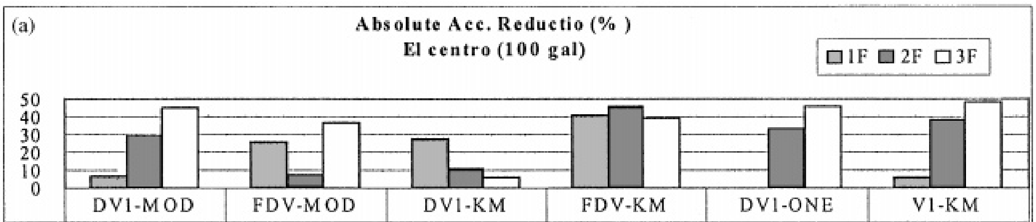
Control parameter	$Q=\left[\begin{array}{c\|c} 1 & 0 \\ \hline 0 & 1000 \end{array}\right],\quad R=10^{-1\cdot 2},$ $Q_i=\begin{bmatrix} 10^{2\cdot 5} & 1 & 1 & 1 & 1 & 1 \\ 1 & 10^{2\cdot 5} & 0 & 1 & 0 & 0 \\ 1 & 0 & 10^{2\cdot 5} & 1 & 0 & 0 \\ 1 & 1 & 1 & 10^{2\cdot 5} & 1 & 1 \\ 1 & 0 & 0 & 1 & 10^{2\cdot 5} & 0 \\ 1 & 0 & 0 & 1 & 0 & 10^{2\cdot 5} \end{bmatrix}$
Control gain (kg/m, kg s/m)	(5019·07, −12 268·92)
Controlled natural frequency (Hz)	(1·1081, 3·5841, 5·7081)
Controlled damping ratio (%)	(10·30, 20·96, 10·59)
Relative disp. reduction (100 gal E1 Centro)	(51·63, 51·88, 53·04)
Maximum control force (100 gal E1 Centro)	8·2046 kN

Table V. Control parameter of case 4 (v1_km)

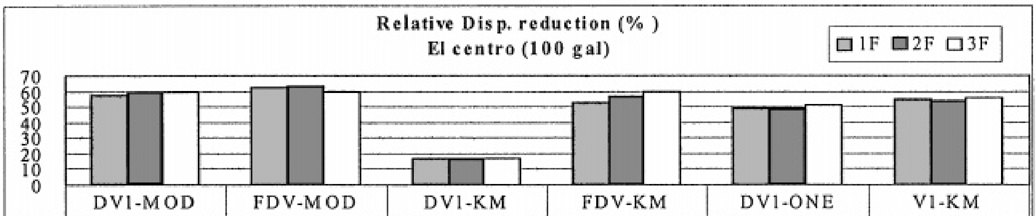
Control parameter	$Q=\left[\begin{array}{c\|c} K & 0 \\ \hline 0 & M \end{array}\right],\quad R=10^{-2\cdot 6912},$ $Q_i=\begin{bmatrix} 10^{2\cdot 5} & 0 & 0 & 1 & 0 & 0 \\ 0 & 10^{2\cdot 5} & 0 & 1 & 0 & 0 \\ 0 & 0 & 10^{2\cdot 5} & 1 & 0 & 0 \\ 1 & 1 & 1 & 10^{2\cdot 5} & 1 & 1 \\ 0 & 0 & 0 & 1 & 10^{2\cdot 5} & 0 \\ 0 & 0 & 0 & 1 & 0 & 10^{2\cdot 5} \end{bmatrix}$
Control gain (kg s/m)	(− 16 000)
Controlled natural frequency (Hz)	(1·1260, 3·6775, 5·5295)
Controlled damping ratio (%)	(10·30, 20·96, 10·59)
Relative disp. reduction (100 gal E1 Centro)	(56·58, 55·79, 56·39)
Maximum control force (100 gal E1 Centro)	9·3548 kN

active brace system as controller were proved to be very effective in structural control, especially on the reduction of relative displacement (50–60 per cent reduction was achieved in each case). From Tables I–V, by checking the structural system parameter before and after the control we found that all the control methods were designed to increase the damping of the structure system, and without modifying the structural natural frequency significantly. The static-output-feedback control method will slightly increase the first fundamental modal frequency about 6 per cent (from 1·096 to 1·165 Hz).

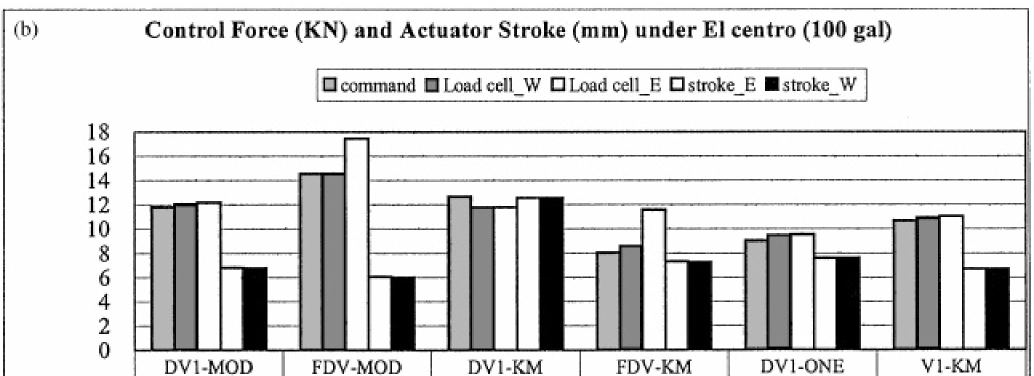
Figures 4(a) and 4(b) show the comparison on the absolute acceleration and the relative displacement of the test structure by using static output feedback LQR control algorithm



	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
1F	6.85	25.52	27.45	40.42	0.22	5.68
2F	29.43	7.78	10.69	45.76	32.95	38.57
3F	45.19	36.34	5.95	39.29	45.97	48.70

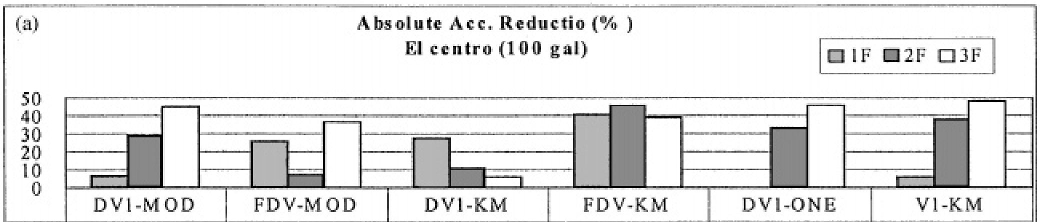


	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
1F	57.52	62.78	17.08	53.18	48.93	54.41
2F	59.90	63.61	17.22	56.35	48.89	54.33
3F	59.37	59.95	17.50	59.20	50.94	56.05

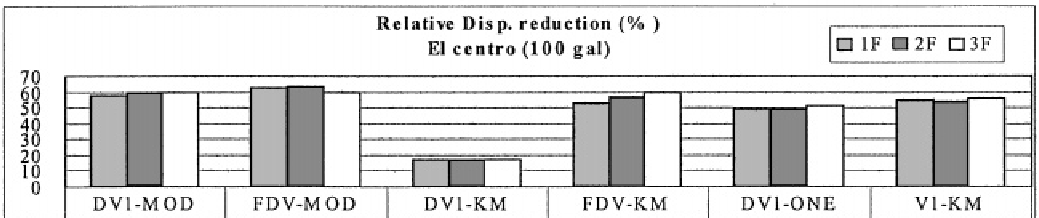


	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
command	11.81	14.57	12.67	8.05	9.03	10.67
Load cell_W	12.09	14.61	11.80	8.55	9.47	10.92
Load cell_E	12.17	17.44	11.78	11.59	9.57	11.02
stroke_E	6.82	6.07	12.57	7.33	7.60	6.69
stroke_W	6.75	6.01	12.57	7.25	7.60	6.69

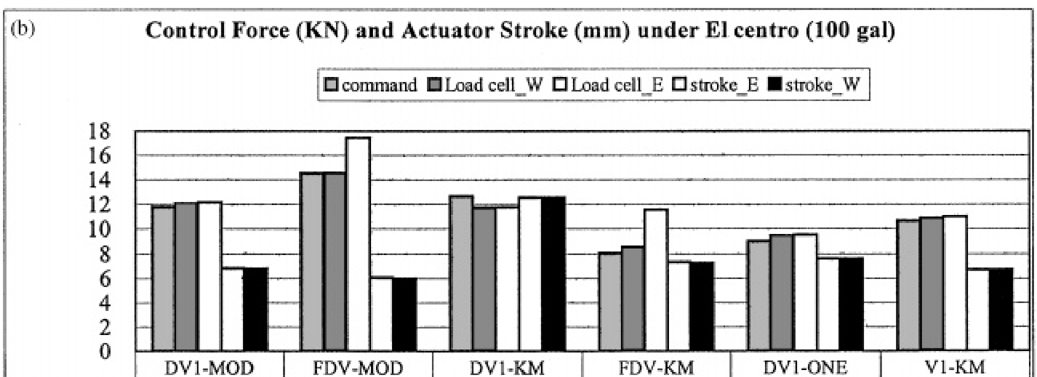
Figure 2. (a) Comparison on the absolute acceleration and displacement of controlled structure using three different control algorithms subjected to E1 Centro earthquake excitation (normalized to 100 gal). (b) Comparison of the required control force and the actuator stroke using three different control algorithms



	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
1F	6.85	25.52	27.45	40.42	0.22	5.68
2F	29.43	7.78	10.69	45.76	32.95	38.57
3F	45.19	36.34	5.95	39.29	45.97	48.70



	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
1F	57.52	62.78	17.08	53.18	48.93	54.41
2F	59.90	63.61	17.22	56.35	48.89	54.33
3F	59.37	59.95	17.50	59.20	50.94	56.05



	DV1-MOD	FDV-MOD	DV1-KM	FDV-KM	DV1-ONE	V1-KM
command	11.81	14.57	12.67	8.05	9.03	10.67
Load cell_W	12.09	14.61	11.80	8.55	9.47	10.92
Load cell_E	12.17	17.44	11.78	11.59	9.57	11.02
stroke_E	6.82	6.07	12.57	7.33	7.60	6.69
stroke_W	6.75	6.01	12.57	7.25	7.60	6.69

Figure 3. (a) Comparison of the absolute acceleration and displacement of controlled structured using three different control algorithms subjected to Kobe earthquake excitation (normalized to 100 gal). (b) Comparison of the required control force and the actuator stroke using three different control algorithms

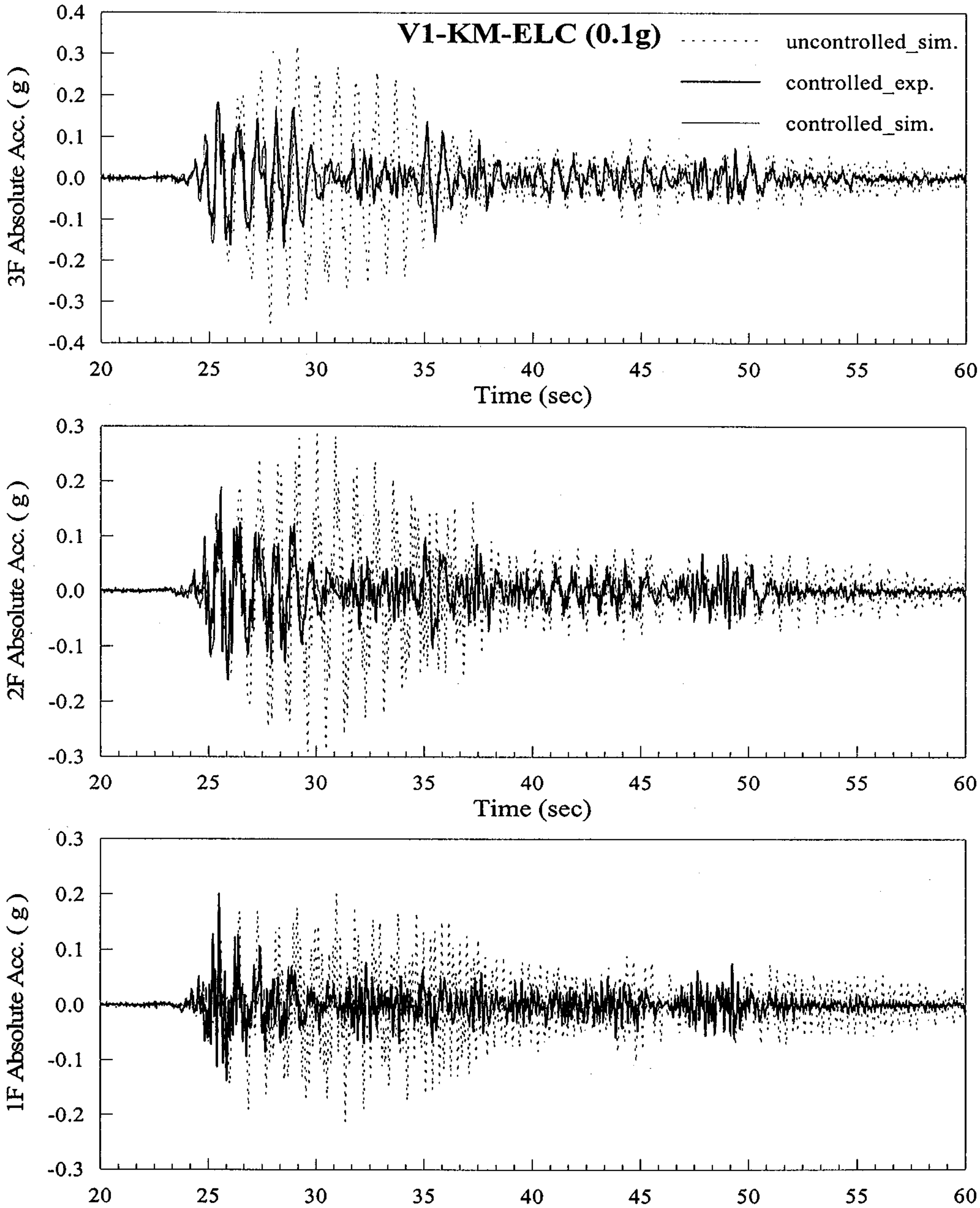
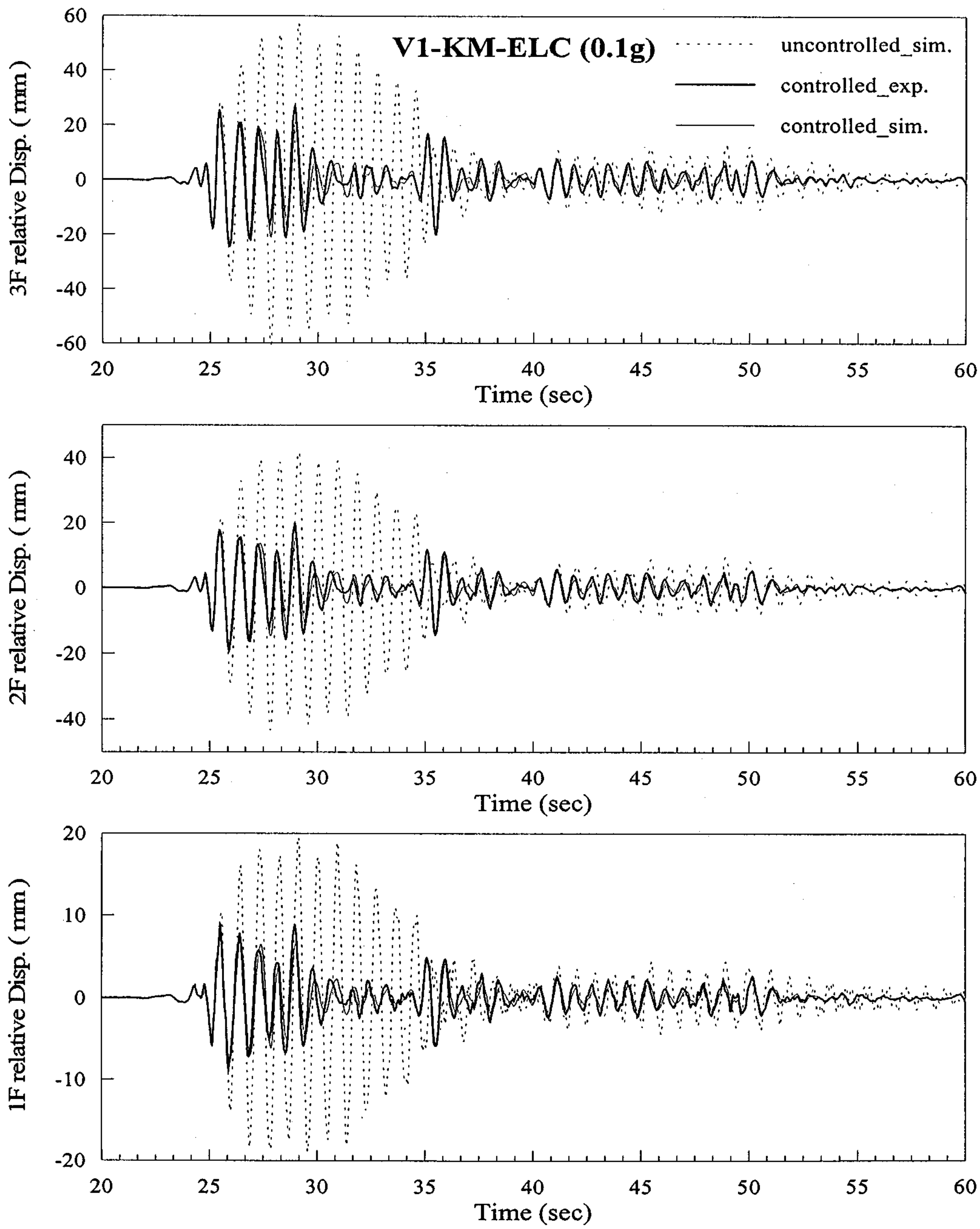
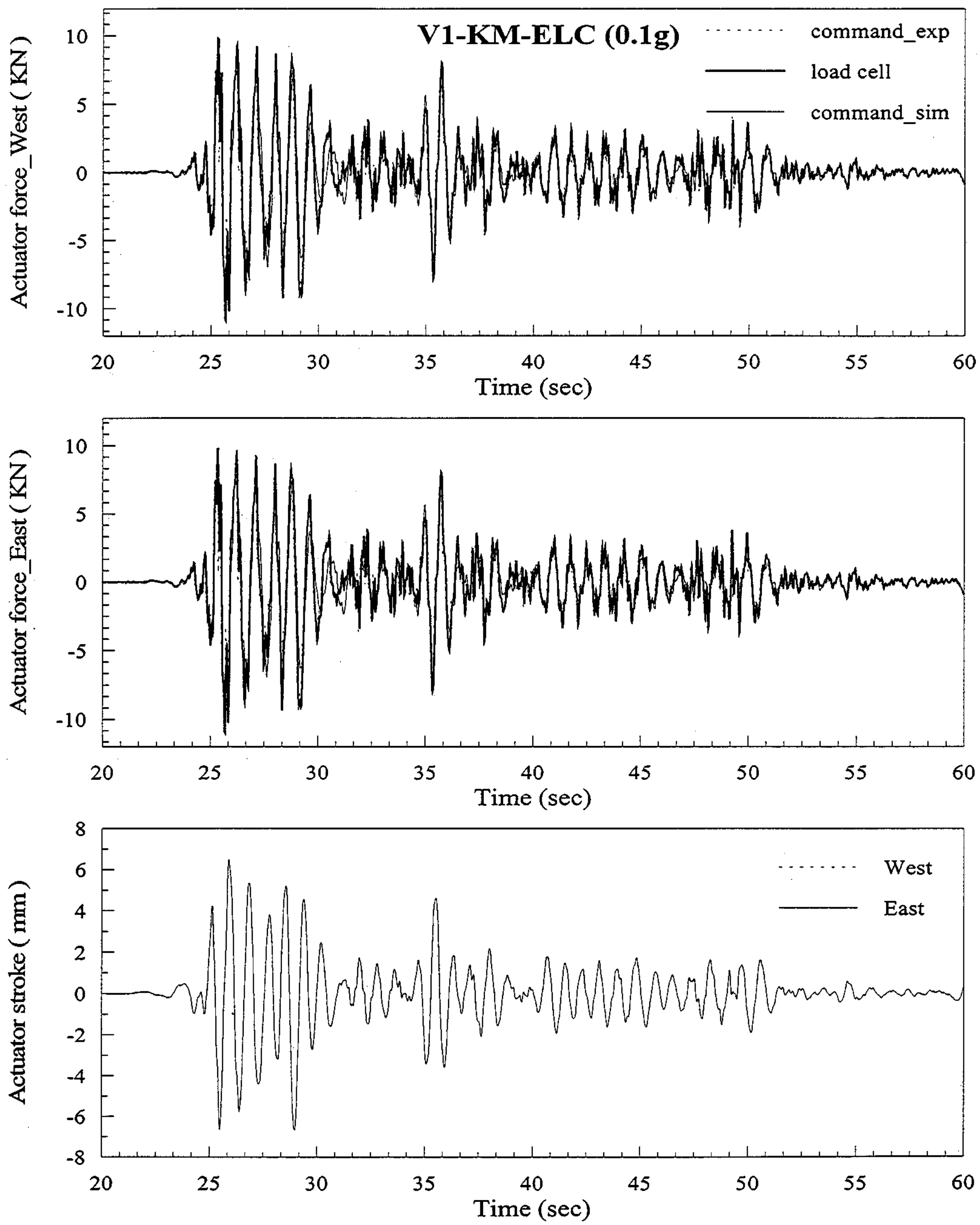


Figure 4. (a) Absolute acceleration time history of static-output-feedback LQR control algorithm under 100 gal E1 Centro earthquake. (b) Relative displacement time history of static-output-feedback LQR control algorithm under 100 gal E1 Centro earthquake. (c) Control force and actuator stroke time history from static output feedback LQR control algorithm under 100 gal E1 Centro earthquake. (d) Fourier amplitude of floor absolute acceleration. Results from static-output-feedback LQR control algorithm under 100 gal E1 Centro earthquake were used. (e) Fourier amplitude of floor relative displacement. Results from static-output-feedback LQR control algorithm under 100 gal E1 Centro earthquake were used



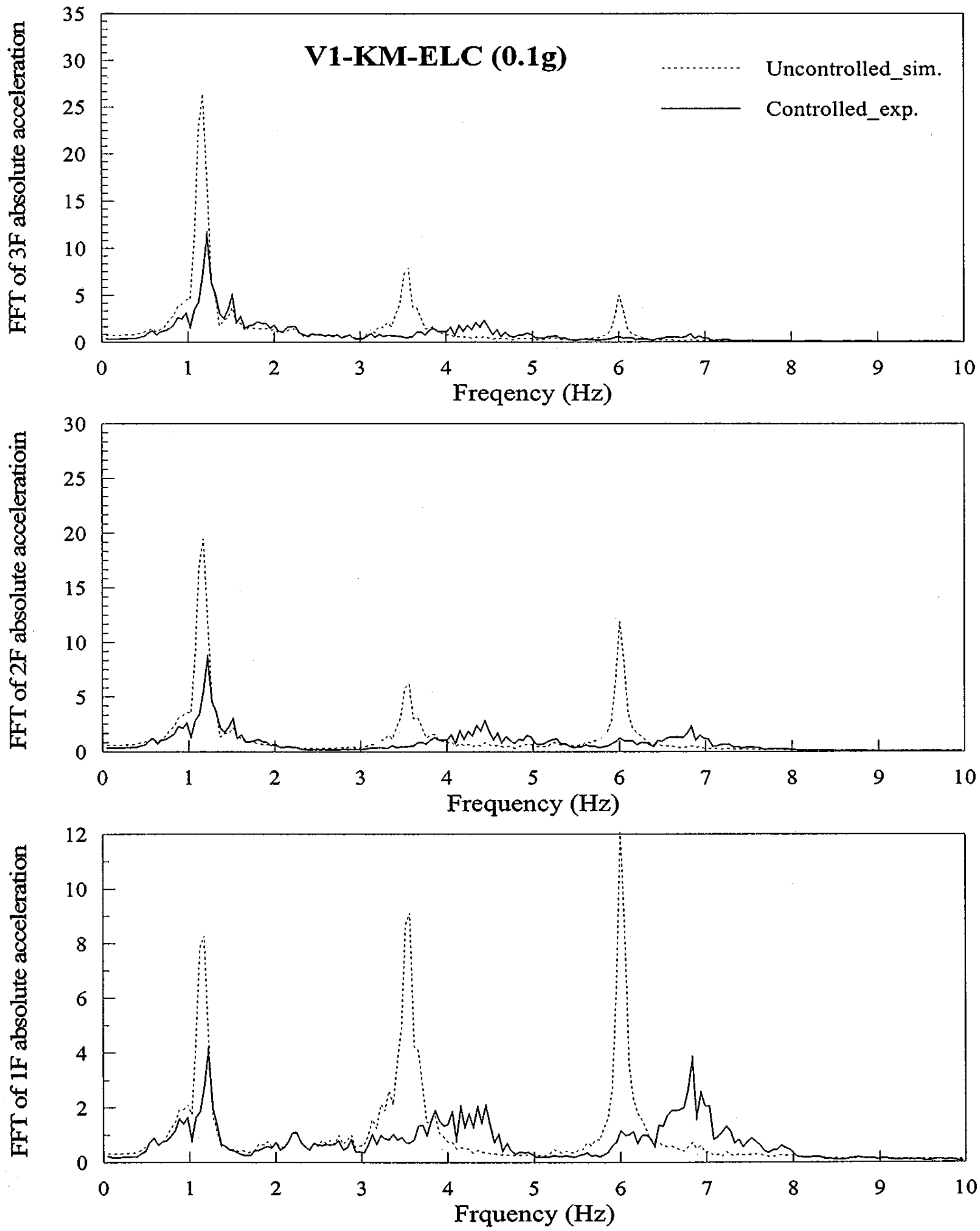
(b)

Figure 4. Continued



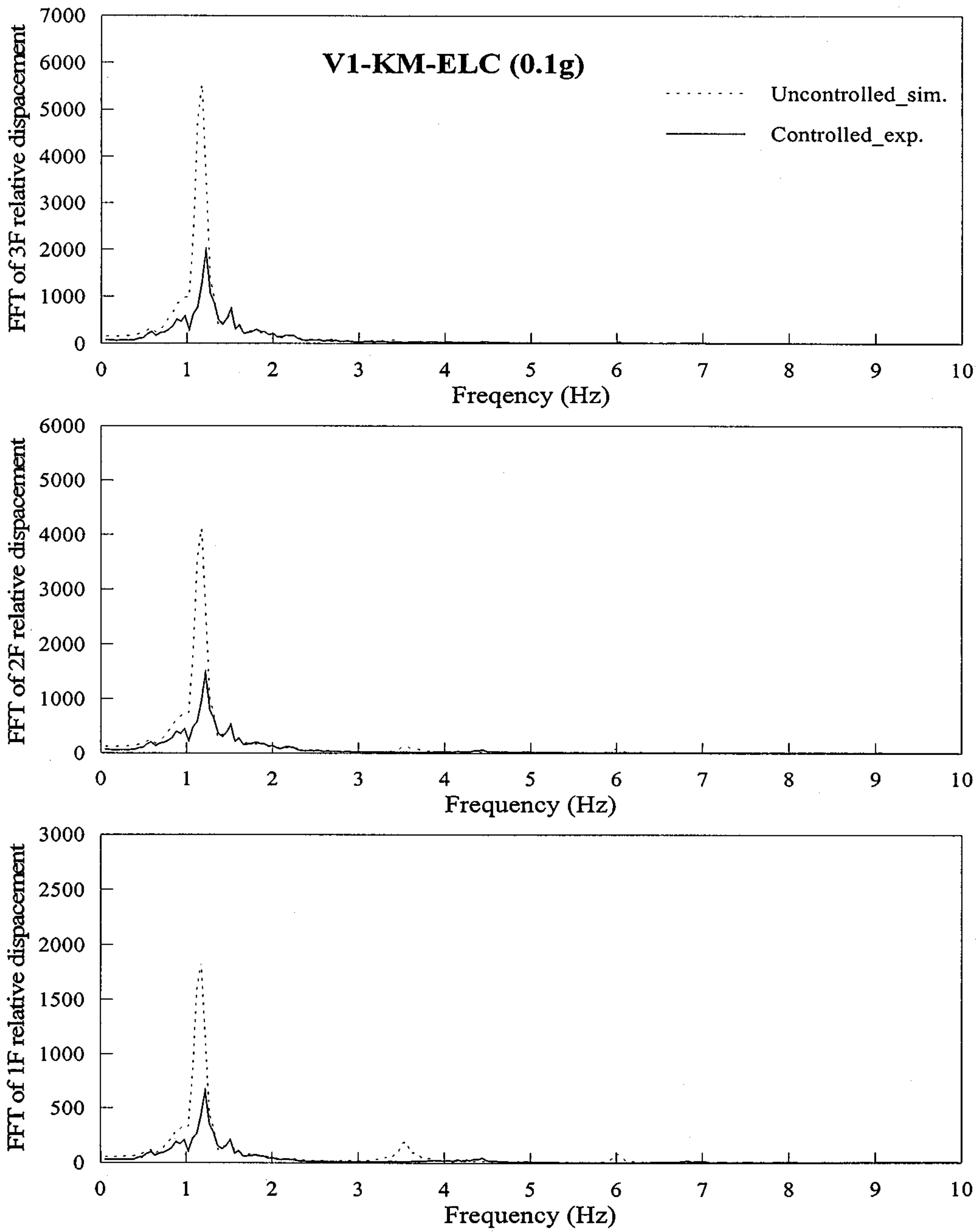
(c)

Figure 4. Continued



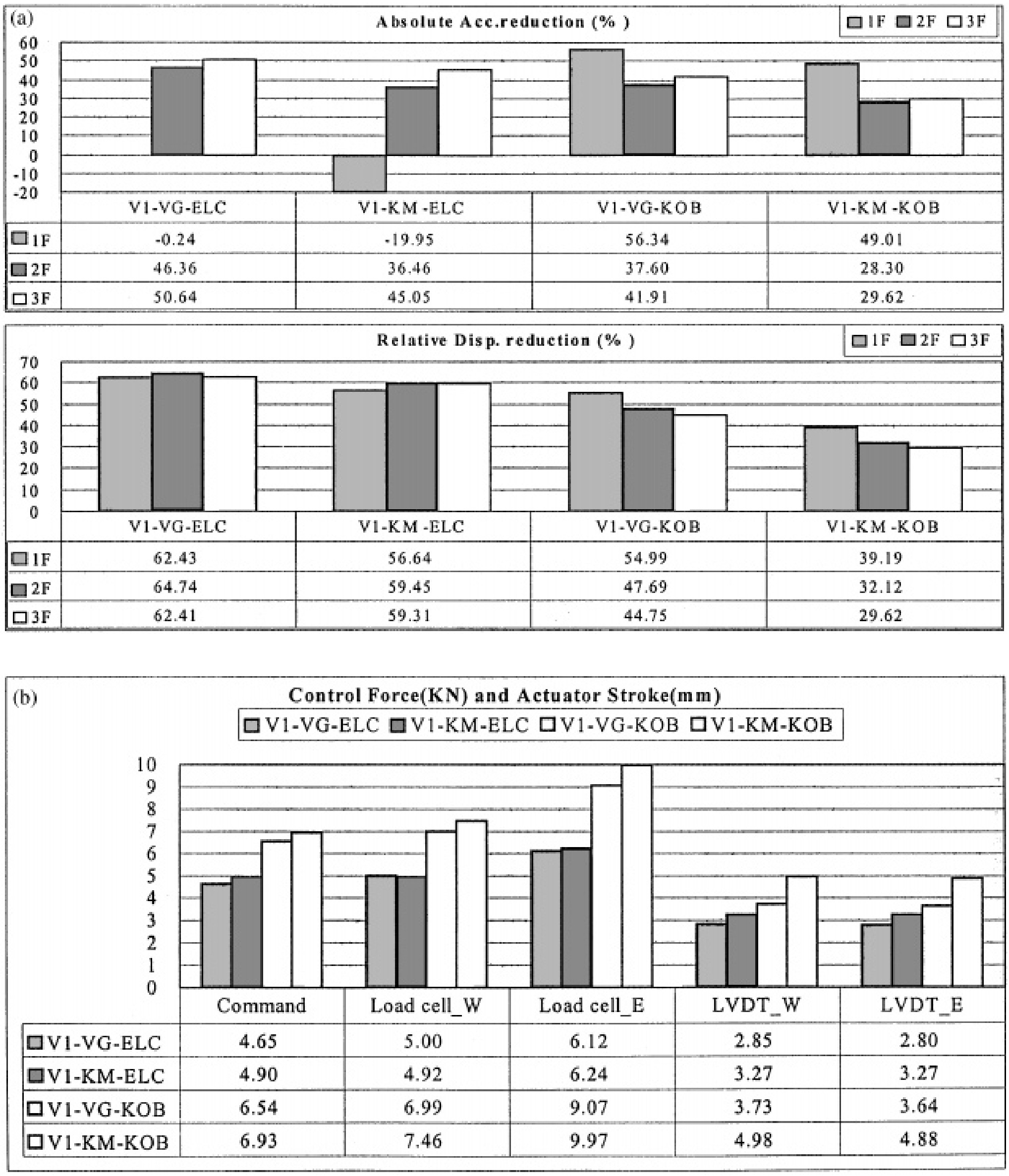
(d)

Figure 4. Continued



(e)

Figure 4. Continued



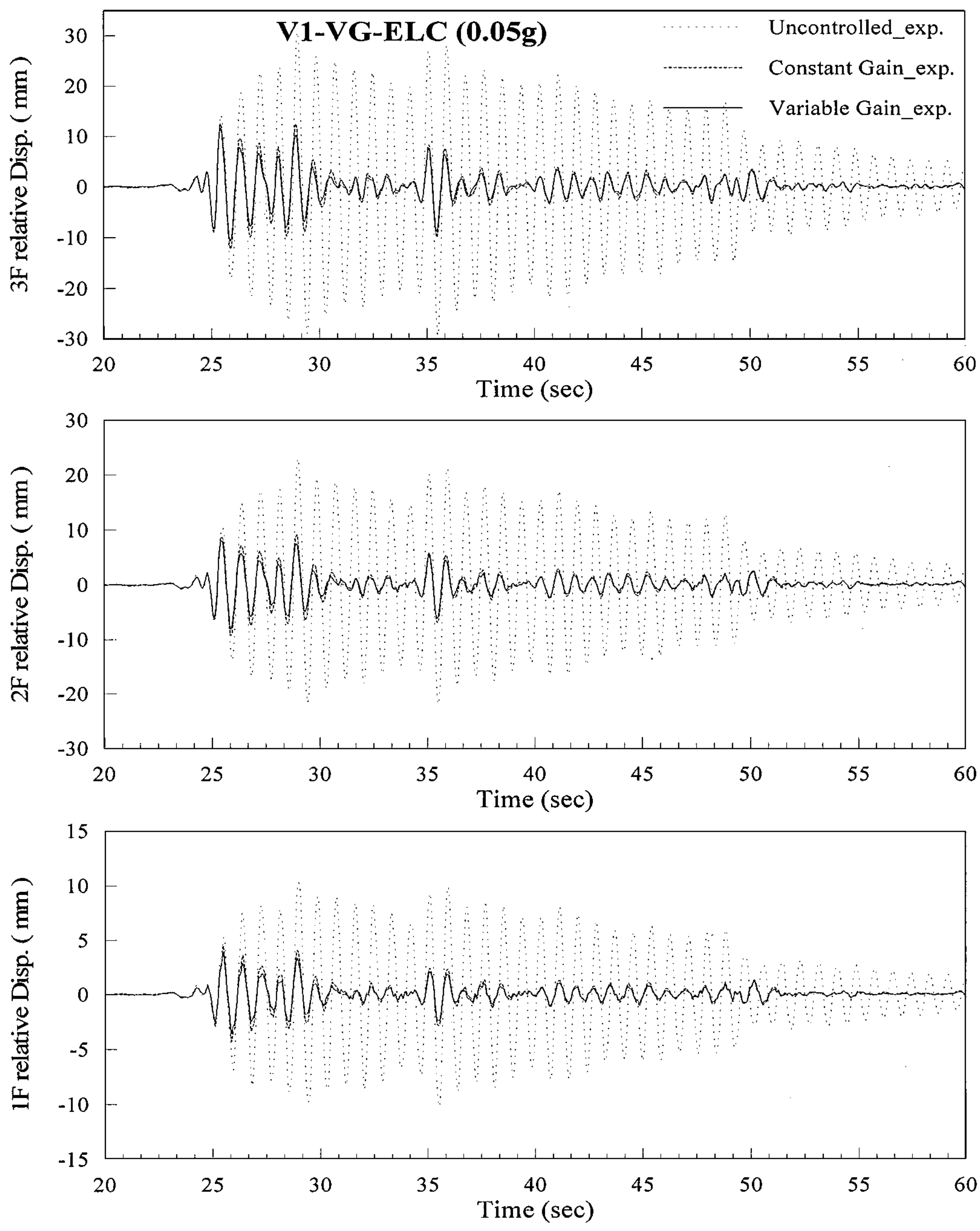
	V1-VG-ELC	V1-KM -ELC	V1-VG-KOB	V1-KM -KOB
1F	-0.24	-19.95	56.34	49.01
2F	46.36	36.46	37.60	28.30
3F	50.64	45.05	41.91	29.62

	V1-VG-ELC	V1-KM -ELC	V1-VG-KOB	V1-KM -KOB
1F	62.43	56.64	54.99	39.19
2F	64.74	59.45	47.69	32.12
3F	62.41	59.31	44.75	29.62

	Command	Load cell_W	Load cell_E	LVDT_W	LVDT_E
V1-VG-ELC	4.65	5.00	6.12	2.85	2.80
V1-KM-ELC	4.90	4.92	6.24	3.27	3.27
V1-VG-KOB	6.54	6.99	9.07	3.73	3.64
V1-KM-KOB	6.93	7.46	9.97	4.98	4.88

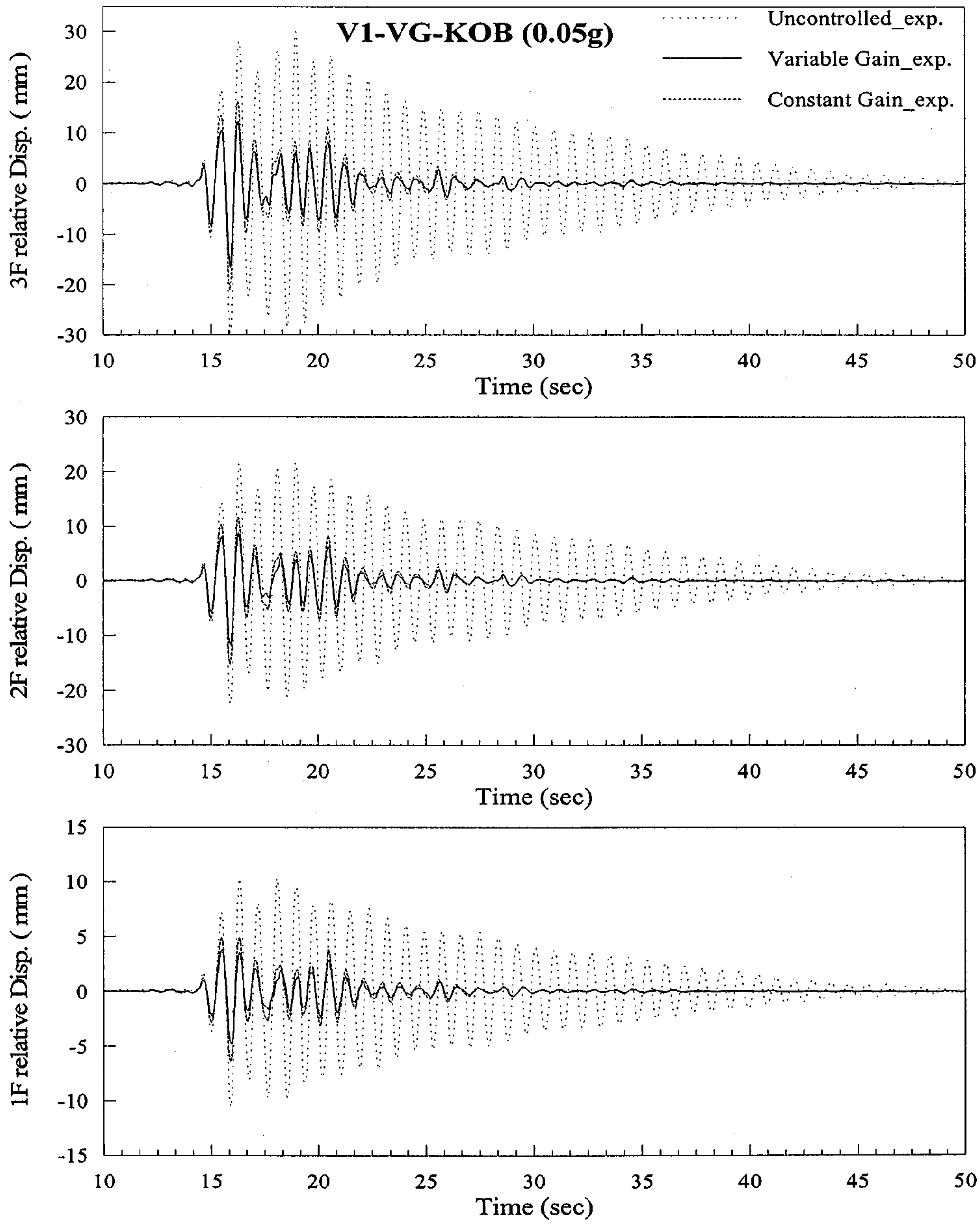
Figure 5. (a) Comparison on the absolute acceleration and relative displacement using two different control methods: variable gain control and static-output-feedback LQR control algorithm (50 gal E1 centro and Kobe). (b) Comparison on the control force and actuator stroke between V1-VG case and V1-KM case

(experimental and simulated result). Figure 4(c) shows control force time history which includes command (experimental and simulated) and load cell response from actuator as well as the actuator stroke time history measure by LVDT. Based on the implementation of the active bracing system and by testing it on the shaking table the results show that the control algorithms



(a)

Figure 6. (a) Comparison of relative floor displacement among three different control methods: without control, constant gain method (V1-KM case) and variable gain method re The E1 centro earthquake (normalized to 50 gal) was used as input. (b) Comparison of relative floor displacement among three different control methods: without control, constant gain method (V1-KM case) and variable gain method re The Kobe earthquake (normalized to 50 gal) was used as input



(b)

Figure 6. Continued

are very effective and the response of active bracing system is so fast that there is no need to consider the time delay problem. Figures 4(d) and 4(e) show the Fourier transform of floor response from Figures 4(a) and 4(b). It is found that the fourier amplitude at dominant frequency of the control system was significantly reduced both in absolute acceleration and relative displacement. In addition, the dominant frequency of the controlled response was slightly shifted to higher frequency because of the stiffness of the bracing system. Comparing these six cases, the control algorithm using only first floor relative velocity as feedback was the simplest one and can reach almost the same control effectiveness as the case using full-state feedback.

The effectiveness of the static-output-feedback control with variable gain was also examined using the same input motion. Figure 5 shows the comparison on the percentage of floor response reduction between static-output-feedback control with variable gain (V1-VG method) and static-output-feedback LQR control (V1-KM method). It seems that the static-output-feedback control with variable gain can reach a better control effectiveness, and less control forces are needed as compared to other methods. Figure 6 shows the comparison on the floor response for system with and without control.

4. CONCLUSIONS

The purpose of this study is to conduct the active structural control experiment and to verify the current state-of-the-art control algorithm by using a full-scale building with active bracing control devices. The experiment was conducted at NCREE lab on a $5^m \times 5^m$ six degrees of freedom shaking table. Through the experiment the following conclusions are drawn:

1. After the shaking table test the active bracing control system proved to be an effective tool in the verification of structural control algorithm against earthquake excitation. It can reduce relative displacement response up to 50 per cent, and also reduce absolute acceleration floor response significantly.
2. It is proved that the modal control algorithm and the static-output-feedback control algorithms can almost achieve the same control efficiency. As compared to the full-state feedback, either the first floor velocity response or the displacement response which is considered as feedback can also reach almost the same good control efficiency.
3. In modal control with direct output feedback case, a pair of feedback was needed (first floor velocity and displacement responses) but in the static-output-feedback LQR control algorithm only the first floor relative velocity can be used as feedback. Although modal control has its limitation on the feedback signal, it is one of the most simple and stable methods to control.
4. Variable gain control is also proved to be effective in this experiment. One only needs to choose a series of different level of control gain, from high to low, and a maximum control force (limited by control device), and the variable gain control method will shift automatically to all kinds of excitations. Using traditional control method to calculate constant gain one needs to consider the limitation of the maximum force in order to protect the system but the variable gain method can automatically decrease control force step by step when it exceeds the limit value.

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